

CALCULATION AND MEASUREMENT OF EXPOSURE BUILDUP FACTORS FOR X-RAY RADIOGRAPHY

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INTRODUCTION

An x-ray radiographic image is generated by both uncollided and scattered photons. The uncollided flux contribution to the image can be estimated straightforward using the attenuation coefficients of the materials used in the radiography. The scattered flux contribution however, is usually accounted for using Monte Carlo techniques or by solving the Boltzmann transport equation for photons [1]. Both of these approaches are computationally expensive and hence can not be incorporated in radiography simulation models for practical limitations.

A powerful x-ray radiography simulation code "XRSIM" was developed here at the Center for Nondestructive Evaluation at Iowa State University. The simulation code utilizes a CAD interface to simulate radiography of objects with complex geometries. Interaction with a CAD interface enables the code of simulating the radiography of any object with no limits on the geometrical complexity of the sample. However, the execution time of the code increases as the complexity of the object increases. Nevertheless, the execution time is still in the order of couple of minutes for objects with very complex geometries.

The simulation code in its current status, uses only the uncollided flux to generate the radiographic image. An attempt to modify the code to account for the scattering contribution to the image using Monte Carlo techniques has shown limited success. Accounting for scattering using Monte Carlo approach increased the execution time of the code from less than two minutes to several hours depending on the geometrical complexity of the radiographed object. A way to get around the inefficiency of Monte Carlo approach is to use the "exposure buildup factors" to account for the effect of scattering. This is an approximate solution but computationally very efficient and can be easily incorporated in the simulation code XRSIM.

DEFINITION OF BUILDUP FACTORS

Buildup factors use the calculated uncollided flux to predict the total flux. Traditionally, they are defined as the ratio of the exposure due to the total flux "uncollided + scattered" to the exposure due to the uncollided flux. Usually; buildup factors are calculated using Monte Carlo methods for a specific material at a certain thickness computed at a certain energy of a monoenergetic incident radiations [2]. However in x-ray radiography the incident radiation has a white spectrum of energies ranging from zero to the tube voltage. Therefore the need arises to introduce a new set of buildup factors that approximate the effect of scattering of a white spectrum of incident radiations.

These new factors have been measured experimentally and then a Monte Carlo code was tuned to reproduce the experimentally measured values. The Monte Carlo code calculates these factors from the basic physical principles by simulating the interactions of the bremsstrahlung spectrum with the object material.

EXPERIMENTAL PROCEDURE

The experimental procedure to measure the exposure buildup factors for an x-ray white spectrum consists of the following steps:

1. Calibration of the x-ray film: Calibrating the x-ray film is to find a relationship between the amount of energy deposited on the film and the resulting optical density. When x-ray photons fall upon the film, the silver halide crystals is activated and when the film is place in the developer the activated crystals are preferentially reduced to produce metallic silver. The amount of metallic silver produced is proportional to the amount of energy deposited on the film. The term "exposure" is used to measure the effect of photons on a body at any point. This effect is proportional to the number of ions produced in the air at a point outside the body. The number of ions produced is an indirect measure of the amount of energy deposited in the body/film. The unit of exposure is *roentgen*, abbreviated R. The exposure "X" is given by the following equation:

$$X = 1.83 * 10^{-8} \sum_i \Phi_i E_i \left(\frac{\mu_a}{\rho}\right)_i^{air} mR \quad (1)$$

in this equation, the x-ray fluence Φ must be expressed in *photons/cm²*, E_i is the photon energy bin in KeV, and $(\frac{\mu_a}{\rho})_i^{air}$ is the mass absorption coefficient of air at the incident energy E_i in units of *cm²/g*. To get the total exposure, the summation in the above equation must be carried for all the energy bins in the x-ray spectrum [2]. The calibration was carried out at a tube voltage of 100KeV, but to get a more complete set of buildup factors, the calibration should be repeated at several other energies as well.

As shown in the experimental setup in figure 1, the x-ray white spectrum that went through the collimator can be detected using the high purity germanium (HPGe) detector and then divided into discrete energy bins using the multi-channel analyzer (MCA). The whole data acquisition system is controlled via a personnel computer and the output is a list of energy bins and

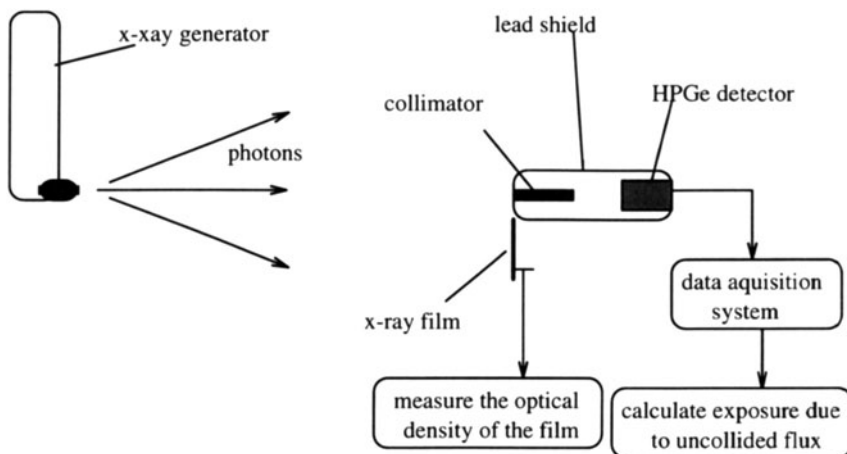


Figure 1. Experimental set up for measuring the exposure buildup factors

their corresponding photons fluences. Equation 1 is then used to calculate the resulting exposure. At the same time, the x-ray film is developed and the optical density of the film is measured using a digital densitometer.

The resulting calibration curve relates the exposure (the amount of energy deposited on the film due to the white x-ray spectrum) to the film optical density. The process was repeated for several exposures and a calibration curve was generated.

2. The next step is to actually measure buildup factors for a certain material. Place a plate of the material of interest (aluminum for example), in front of the detector and the x-ray film using the same experimental setup as in step 1. Expose the plate using a certain tube voltage (say 100KV). The photons that went through the plate and into the collimator are the uncollided photons, while the resulting film density is due to both the uncollided and the scattered fluxes.
3. The calibration curve generated in step1 is used to find the film density that corresponds to the uncollided flux from step 2, while the density that corresponds to the total flux is measured directly from the film.
4. Find the "exposure buildup factor" defined as :

$$B(\text{energy, material, thickness}) = \frac{\text{density due to total flux}}{\text{density due to uncollided flux}} \quad (2)$$

This is the buildup factor for a certain material of thickness X when exposed to a white x-ray spectrum generated from a specific tube voltage.

5. Repeat steps 2 and 4 for other aluminum thicknesses (say 0.5, 0.75, 1.0, 2.0 inches). This will generate buildup factors for aluminum at different thicknesses for a white spectrum of x-rays with a maximum energy of 100KeV.
6. Repeat the experiment for other tube voltages.
7. Repeat the experiment for other materials.

The resulting buildup factors are functions of the x-ray tube voltage, the thickness and the material type of the object used in the radiography.

THE SIMULATION CODE

Measuring buildup factors experimentally is a very exhaustive, expensive and time consuming process. A more convenient way to generate tables of these factors is to use a simulation code. To generate tables of buildup factors, we have developed a code based on Monte Carlo technique for photon transportation that uses the basic physical principle of photon interaction with matter to calculate buildup factors. To give the code more generality we have incorporated in it a simulation of the x-ray generator itself to simulate a bremsstrahlung spectrum.

The simulation code starts by calculating the parameters that governs the type of interaction of photon with matter, namely the photon energy and its mean free path (mfp). In the energy ranges of interest in radiography, the two interactions that most likely to take place are photoelectric absorption and Compton scattering. In the photoelectric interaction, the photon disappears and the process of tracking its path is terminated. However; if the interaction is a Compton scattering, the photon will continue to wander around in the object until it gets absorbed or it exits the object in the direction of the film or in any other direction. In this case the code will trace the photon by calculating its scattering angle and energy and a new mfp. The values of the scattering energy and angle are governed by the Klein-Nishina formula for the Compton scattering differential cross section:

$$\frac{d\Sigma_{Compt}}{d\varepsilon} = \frac{X_o n \pi r_o^2 m}{E_o} \left(\frac{1}{\varepsilon} + \varepsilon \right) \left(1 - \frac{\varepsilon \sin^2 \theta}{1 + \varepsilon^2} \right) \quad (3)$$

where

X_o = mean free path of photons in the object (cm),

n = electron density (electron/cm³),

r_o = classical electron radius (cm),

m = electron rest energy (MeV),

E_o = incident photon energy (MeV),

E = scattered photon energy,

$\varepsilon = E/E_o$, and

θ = is the scattering angle.

The initial energy of the incident photon is sampled from a bremsstrahlung spectrum according to the relative intensities of photons in the energy bins. Then, we calculate the mfp that corresponds to the incident energy. If the mfp is greater than the sample thickness, the photon will exit the sample. If it hits the film, the code will convert its energy into exposure using equation 1 and start all over again. However, if the mfp is less than the sample thickness, the photon will interact with the sample material. If the interaction is a Compton scattering, we randomly sample the variable ε in equation 3, which is a measure of the energy of the scattered photon. The two extreme values of the energy of the scattered photon correspond to a scattering angles of 0 and 180 and consequently ε is:

$$\frac{1}{1 + \frac{2E_\gamma}{m}} < \varepsilon < 1 \quad (4)$$

The last term in equation 3 is called the rejection function $g(\varepsilon)$, to calculate that we need to find the angle of scattering. This is given by the Compton scattering

formula:

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma/mc^2)(1 - \cos \theta)} \quad (5)$$

solve equation 5 for θ and calculate the rejection function $g(\epsilon)$. If a randomly generated number ψ is less than the rejection function, then the combination of energy and angle picked does not satisfy equation 3. Reject the combination and repeat the process by sampling a new scattering energy and calculating a new scattering angle [3]. After selecting the energy and the angle of the scattered photon, the azimuth angle is isotropic and randomly sampled between 0 and 360°. A look up table is then used to find the corresponding photon interaction cross sections and calculate the new mfp before the next scattering event. The process is repeated until the photon is either absorbed or exits the object.

Finally, when photons exit the object in the direction of the film, their kinetic energy is converted into exposure using equation 1. A flag in the code discriminates between the photons that hit the film after scattering and those who went through the object without interaction. Finally, the code calculates a buildup factor for that particular material type and thickness at incident x-ray white spectrum with the specific tube voltage.

DISTRIBUTING THE CODE ON PARALLEL MACHINES

To calculate buildup factors using the code described above, we have to track the histories of several billions of photons. This is because most of the photons in the bremsstrahlung spectrum have very low energies (at least when the tube voltage is below 100 KV), and consequently they get absorbed (via the photo electric absorption) before reaching the film. Photons that get absorbed in the object material, contribute no information for calculating buildup factors. This means that to accumulate enough data to calculate a buildup factor we have to run the code for several days on a DECstation 5000/240. A way to get around this obstacle is to distribute the code to run in parallel on a network of several work stations.

We have used the C-Linda software package to achieve this goal. This software is based on a multiple instruction multiple data (MIMD) parallelization scheme. The C-Linda can be installed on shared and distributed memory machines. In the case of a network of unix work stations, the software specifies one node to be a master node and the rest of the nodes to be workers (slave nodes). The master node works as a coordinator between the slaves. It distributes the work load on the slave nodes by assigning a certain portion of the total number of photons to each one of them. Finally, the master node collects the output of each of the slave nodes, adds them up and calculates a buildup factor. This way, the execution time of the code was cut by a factor almost equal to the total number of slave nodes.

RESULTS

A calibration curve for the KODAK-AA x-ray film was generated. The curve is shown in figure with error bars that represent one standard deviation of the measured density from the mean value. The deviation from the mean increases at higher

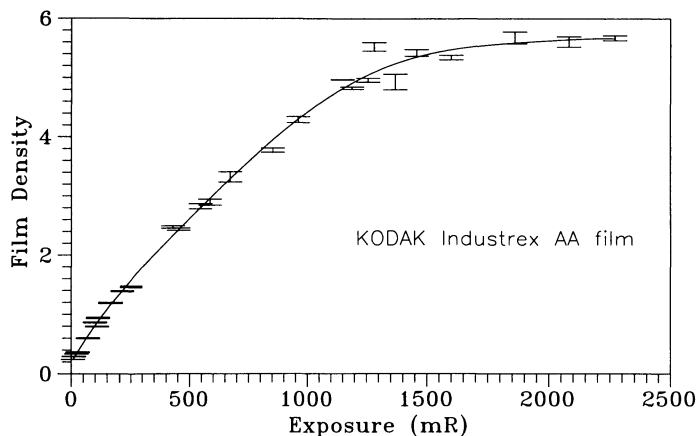


Figure 2. Calibration curve for the KODAK-AA x-ray film at 100KeV

exposures as we approach the saturation density of the film. Experiments were also conducted to measure the exposure buildup factors for aluminum at several thicknesses when exposed to x-ray white spectrum with a maximum energy of 100KeV. The result is shown in figure . As we would expect the buildup factors increase as the thickness of the object increases. The experiments were repeated five times for each thickness, and the error bars show one standard deviation from the average of the sample of five repeats. Also on the same figure shown is the results of the simulation code.

The calculated buildup factors came within 10% of the measured values. However; they are systematically lower than the measured values. A discrepancy due to the fact that only the high energy end of the bremsstrahlung spectrum was used to calculate these factors. This was necessary as the execution time was getting too big as the thickness of the object increases. For example, the execution time for calculating a buildup factor at a thickness of 2 inches was 25 hours on a network of 10 DECstations 5000/240 running in parallel.

Finally, these factors can be calculated off line and tables for several materials can be generated. These tables are then accessed by XRSIM to account for scattering. This way of assessing scattering did not add any significant time to the execution time of XRSIM. For example the two images shown in figure were generated in about 34 and 35 seconds respectively on an alpha DECstation. Image on the left was generated using the UN collided flux only, while for image to the right, buildup factors were used to account for the contribution of the scattered photons.

CONCLUSION AND FUTURE WORK

This paper introduced a computationally efficient method to account for the contribution of scattered photons to a radiographic image. Exposure buildup factors were measured experimentally and a simulation code was developed to reproduce the

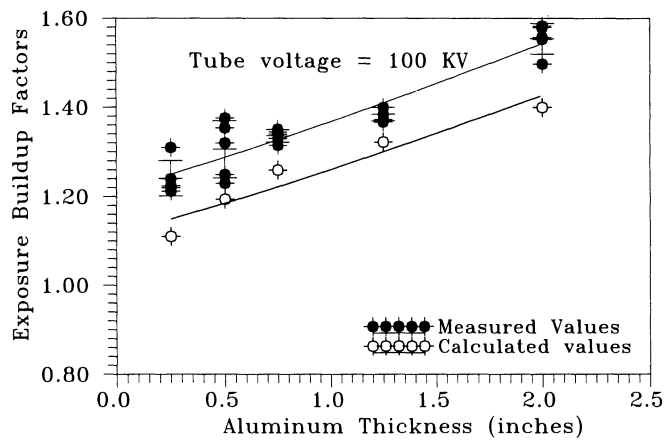


Figure 3. Measured and calculated buildup factors for aluminum

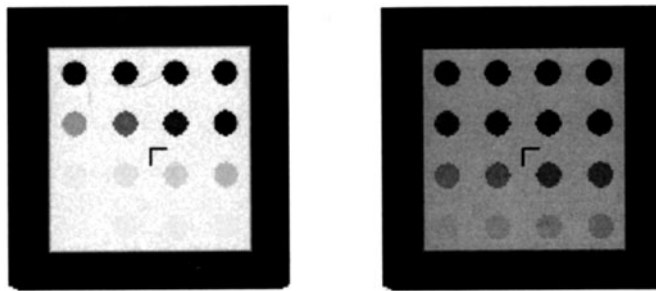


Figure 4. Effect of scattering using buildup factors

measured values. The simulation code can be used to generate lookup tables of these factors for different materials at different energies and thicknesses. The x-ray radiography simulation code XRSIM can now access these tables and a more realistic simulated images can be produced.

A major restriction to using buildup factors to account for scattering is that they are only valid for smooth and well behaving surfaces. In the situation where there is a sudden change in the object thickness or the material type, buildup factors alone can not account for the scattering effect. These situations should be studied further and buildup factors across such changes should be modified to accommodate the uneven scattering of photons from the thicker (or higher density) part to the thinner (or lower density) part of the object.

ACKNOWLEDGMENT

This material is based upon work performed at the FAA Center for Aviation Systems Reliability operated by Iowa State University and supported by the Federal Aviation Administration under grant No. 93-G-018.

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